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Power System Commonality Study (Task Order No. 10, Subtask 1)

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FOREWORD

This report documents the work performed by Rockwell International's Rocketdyne Division on NASA Contract No. NAS3-25808 (Task Order No. 10, Subtask 1) entitled "Power System Commonality Study." This work was performed for the Lewis Research Center (LeRC) of the United States National Aeronautics and Space Administration. The NASA LeRC Task Order Contract Technical Manager was Mr. William A. Poley and the Specific Task Manager was Mr. Robert Cataldo. The Rocketdyne project engineer was Mr. James M. Shoji.

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NOMENCLATURE

AMTEC	=	Alkali metal thermoelectric converter
BIPS	=	Brayton Isotope Power System
BRU	=	Brayton Rotating Unit
CBC	=	closed Brayton cycle
D	=	day
DIPS	=	Dynamic Isotope Power System
FOM	=	figure of merit
GaAs/Ge	=	gallium arsenide on germanium base photovoltaic cell
GPHS	=	General Purpose Heat Source
LEV	=	lunar excursion vehicle
LMCR	=	liquid metal cooled reactor
MEV	=	Mars excursion vehicle
N	=	night
NaS	=	sodium sulfur
NiH_2	=	nickel hydrogen
P	=	peak
PCU	=	power conversion unit
PEM	=	proton exchange membrane
PMAD	=	power management and distribution
PMG	=	permanent magnet motor generator
PVA	=	photovoltaic array
RFC	=	regenerative fuel cell
RTG	=	radioisotope thermoelectric generator
SC	=	Stirling cycle
SD	=	solar dynamic power system
SEI	=	Space Exploration Initiative
ST	=	solar thermal
TE	=	thermoelectric
TI	=	thermionic

1.0 SUMMARY

A limited top level study was completed to determine the commonality of power system/subsystem concepts within potential lunar and Mars surface power system architectures. A list of power system concepts with high commonality was developed which can be used to synthesize power system architectures which minimize development cost. Examples of potential high commonality power system architectures are given in this report along with a mass comparison. Other criteria such as life cycle cost (which includes transportation cost), reliability, safety, risk, and operability should be used in future, more detailed studies to select optimum power system architectures.

Nineteen potential power system concepts were identified and evaluated for planetary surface applications including photovoltaic arrays with energy storage, isotope, and nuclear power systems. A top level environmental factors study was completed to assess environmental impacts on the identified power system concepts for both lunar and Mars applications. Potential power system design solutions for commonality between Mars and lunar applications were identified. Isotope, photovoltaic array (PVA), regenerative fuel cell (RFC), stainless steel liquid-metal cooled reactors (<1033 °K maximum) with dynamic converters, and in-core thermionic reactor systems were found suitable for both lunar and Mars environments. The use of SP-100 thermoelectric (TE) and SP-100 dynamic power systems in a vacuum enclosure may also be possible for Mars applications although several issues need to be investigated further (potential single point failure of enclosure, mass penalty of enclosure and active pumping system, additional installation time and complexity). There are also technical issues involved with development of thermionic reactors (life, serviceability, and adaptibility to other power conversion units). Additional studies are required to determine the optimum reactor concept for Mars applications.

Various screening criteria (availability, environmental compatibility, mass competitiveness of energy storage, safety, and practicality for the application) were used to define concept applicability for each lunar and Mars application. A screening study resulted in 13 power systems for lunar applications and 15 for Mars applications. A commonality analysis showed several power systems with potentially high commonality (across both lunar and Mars applications). These high commonality systems included PVA/RFC, dynamic isotope (1033 °K Stirling, 1133 °K Brayton, and 1300 °K Brayton PCUs), SP-100 TE and dynamic derivatives (Mars systems required vacuum enclosure), in-core thermionic reactor, and liquid metal cooled reactor/Stirling cycle (1033 °K).

The generic commonality results were used to synthesize 3 high commonality power system architectures: (1)predominantly PV (limited nuclear and isotope), (2)predominantly in-core thermionic reactor/DIPS, and (3)predominantly SP-100 reactor/DIPS. The in-core thermionic reactor/DIPS power system architecture had the lowest total mass.

Specific outputs from this study included lists of power system requirements, power system candidates, a power system application matrix, power system characteristics (mass), power system commonality ratings, example high commonality power system architectures, architecture masses, and issues/design solutions for lunar/Mars commonality.

2.0 INTRODUCTION

NASA, as part of the 90 Day Lunar/Mars Study (Refs. 1 and 2), defined a reference mission scenarios as well as reference power systems for each application. NASA and the Synthesis Group are investigating various approaches to development of power systems to meet humankind's renewed effort to explore and eventually colonize the moon and Mars. Of key interest is the reduction in the rather significant costs of this effort. The life cycle cost, including development and transportation costs, must be minimized if this ambitious endeavor is to be realized. In order to achieve this goal, it is necessary to evaluate different development approaches. Power system commonality is one criterion which must be evaluated in order for the optimum power system development roadmap to be developed. How often a given component, subsystem, or system will be used and how early it will be needed in a scenario have a major impact on this development roadmap and hence on development cost.

Certain components and power system concepts are more adaptable to different applications than others. These systems will have a higher commonality figure of merit (FOM) because fewer different power systems and technologies must be developed. This will mean reduced development cost and time. Modular systems (i.e., those consisting of a number of smaller power systems with a standardized power level or single power systems with standardized subsystem modules) have the additional advantages of increased flexibility for the mission designer to meet a wider range of mission requirements as follows:

- excess power capability allows for growth; and
- graceful failure mode (i.e., some power still available if one module fails).

Another benefit of common systems is the reduced astronaut training in system operation and maintenance since many systems will be the same or similar.

This study was a preliminary evaluation of power system and subsystem commonality for manned planetary missions. The NASA 90-Day Study (Refs. 1 and 2) and other literature were reviewed to define a range of missions and power system requirements. The purpose of the study was to identify high commonality power system concepts and to define one or more high commonality power system architectures for further study as part of a future task.

Specific goals identified for this study are as follows:

- selection of practical power systems for each application;
- identification of power system options for lunar/Mars commonality;
- definition of high commonality power system architectures; and
- preliminary assessment of power system architectures.

3.0 TECHNICAL DISCUSSION

The technical discussion includes sections on the study guidelines and assumptions, approach and rating methodology, mission requirements, concept synthesis, environmental impacts on the power systems and design options, power system applicability, generic power system commonality, and power system architecture studies (commonality, mass, advantages/disadvantages).

3.1 GROUNDRULES

The term "architecture" was used in this study to refer to a specific set of power systems (one concept for each application) which met all of the application scenario requirements. Power system concepts were evaluated primarily at the system and subsystem level. Key subsystems included the energy source, power or energy conversion unit, energy storage, heat rejection, and power conditioning (major elements). Only certain subsystem technologies were considered due to the limited scope of this task. Technologies were selected which are currently in some stage of development. The subsystem types included proton exchange membrane (PEM) RFCs, nickel hydrogen (NiH_2) or sodium sulfur (NaS) batteries, gallium arsenide on germanium photovoltaic arrays (GaAs/Ge PVA), plutonium isotope heat sources, liquid metal cooled reactor (LMCR) or in-core thermionic (TI) reactors, heat pipe radiators, and tube sheet radiators (for isotope/Brayton cycle power systems). Power conversion unit options include thermoelectrics, thermionics, Brayton cycle, Stirling cycle, and AMTEC.

Only a limited number of power system architectures were compared. There are only a limited number of power system architectures which make sense from a feasibility, cost, and risk standpoint. These architectures were based primarily on commonality ratings (discussed later) and NASA's 90 day studies (Refs. 1 and 2). An exception to this rule is when only one power system will meet the application requirements. These architectures are not necessarily optimum.

The technology availability (fully flight qualified) timeframes were defined as follows:

- Nearterm (NT) - 1990 to 1999;
- Midterm (MT) - 2000 to 2009;
- Farterm (FT) - 2010 to 2020; and
- Advanced (AD) - 2020 and beyond.

Mobile and portable energy storage systems were assumed to be recharged by the base PVA power system. The impact of the mobile RFC system recharging on the base power system mass was considered.

Other mass study groundrules included the following:

- effect of power system mass on vehicle power requirements or speed was neglected;
- systems were designed to provide both nominal and peak power, if applicable (isotope systems include NaS batteries for peaking power; RFC systems designed to operate at off-design conditions);
- power distribution was not considered (application and power system dependent);
- modular power systems - 2.5 kWe modular isotope/CBC systems and 100 kWe SP-100 thermoelectric systems;
- scaled systems - PVA/RFC, RFC, and in-core thermionic; and
- reactors are buried.

3.2 APPROACH AND RATING METHODOLOGY

The approach taken during this study is shown in Figure 1. The first step was to identify the activities requiring separate power supplies. Once these options were identified, then power system requirements were identified for each activity.

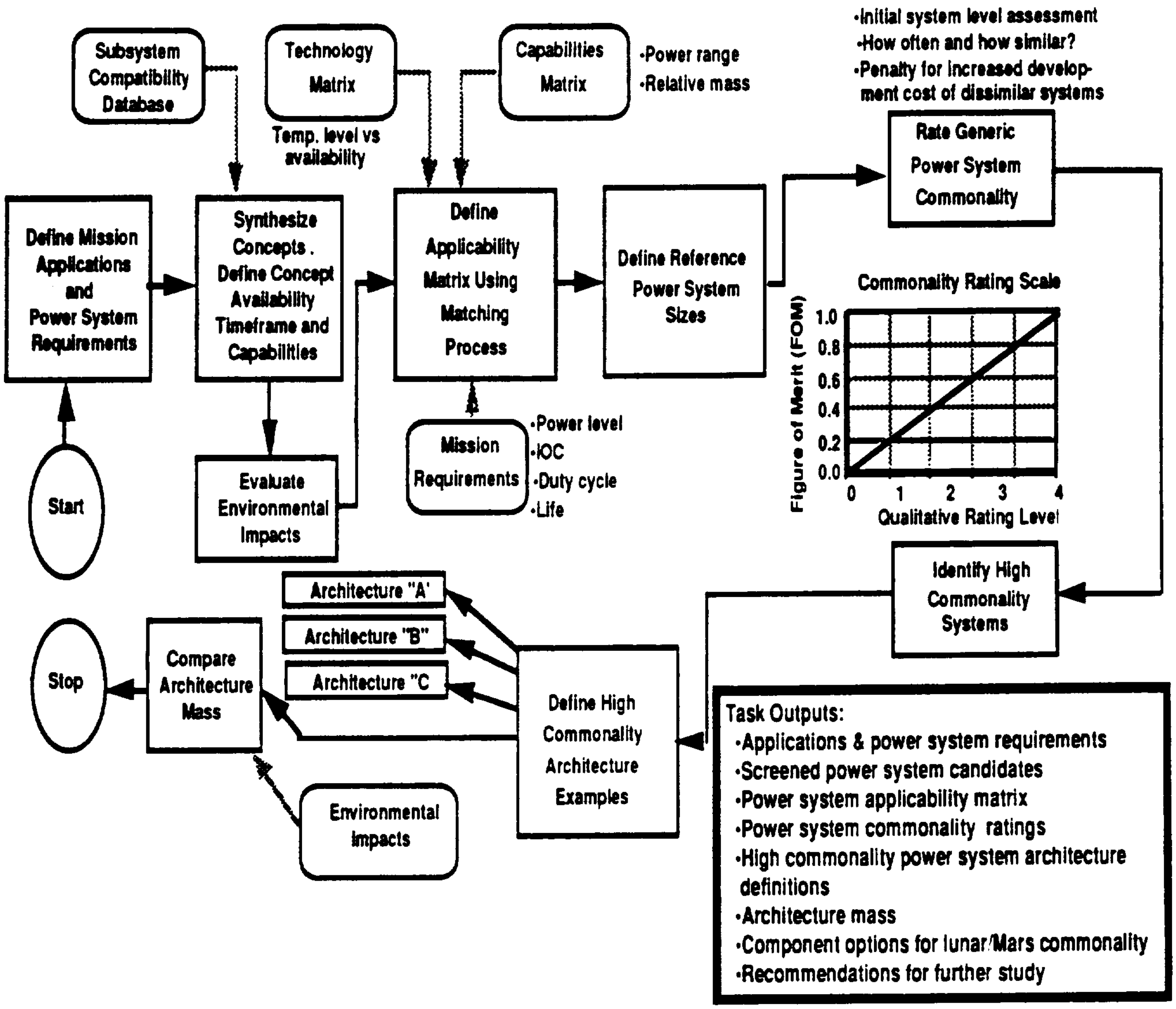

Figure 1. - Task approach logic flow diagram.

Next, potential subsystem design options were identified which might be applicable to planetary systems. A subsystem compatibility matrix was used to synthesize 19 different practical power system concepts. The earliest each system would be available was then estimated. Power system capabilities were also determined in terms of power ranges and peak temperature levels. Each planetary activity was assigned an availability requirement based on the earliest IOC date. A power system applicability matrix was then defined by comparing activity requirements with power system availability and capabilities. Various screening criteria were used to determine if a power system could be reasonably used for a given application.

Reference power systems were then defined for each concept. The purpose of the reference systems was to assess on a qualitative basis the amount of extra development effort required to develop a power system for a given application. A linear figure of merit (FOM) scale was developed for the commonality ratings to reflect the different levels of the simple subjective evaluation. The commonality (how often each power system can be applied) was then assessed for each power system and application using the modularity FOM (qualitative development cost impact for power system changes relative to baseline) as a derating factor (0 to 1.0). The power systems were then grouped on the basis of the commonality ratings.

The systems with the highest overall commonality ratings and which had good ratings for both lunar and Mars missions were then utilized to synthesize power system architecture examples. The highest peak temperatures consistent with the application IOC for power systems with dynamic conversion units were used. The power system architectures were designed for high commonality in order to minimize development costs, although costs were not factored into this analysis.

The power system architectures were then evaluated. Power system masses and total architecture mass were determined. Environmental impacts of power system mass for Mars systems were included in the mass studies.

3.3 POWER SYSTEM REQUIREMENTS

A hybrid of the NASA mission options from the 90-Day Study was selected as the framework for determining lunar and Mars power system requirements. The combination of applications (power loads) was referred to as a "scenario" in this study and did not include any specific power system options. The mission scenario was divided into 3 phases for the lunar portion (emplacement, consolidation, and operations) and 4 phases for the Mars portion (exploration, emplacement, consolidation, and operations).

The Lunar Emplacement Phase (1999-2002) will involve initial setup of the base. Lunar emplacement will require power systems for communications (L1), 3 fixed power systems (L2) to provide life support and lab module power, an emergency power system (L3), the first LEV servicer (L4), the payload unloader (L7), and 2 unpressurized rovers (L8; manned or unmanned operation).

The Lunar Consolidation Phase (2003-2007) expands the crew activities and increases stay time to 6 months. Lunar Consolidation will require power systems for base power (L5), a second LEV servicer (L4), another unpressurized rover (L8), and a pressurized rover (L9).

The Lunar Operations Phase (2008 and beyond) expands science activities, begins utilization of insitu resources, and moves the base toward self-sufficiency. Lunar Operations will require power systems for industrial applications (L6), another unpressurized rover (L8), a regolith hauler (L10), and a mining excavator (L11).

The Mars activities begin with the Expedition Phase (Refs.1-4). The purpose of this phase is to find a suitable site for a permanent base. Three initial Mars expeditions to different sites were assumed for this study. This is a worst case combination of the Intermittent Occupancy Option and the Permanent Occupancy Option in terms of the number of power systems required but delays setup of the permanent base. Time is left after the last expedition to study the Mars data obtained from the site explorations and decide which site should be the permanent base. The Mars Emplacement (2022-2023), Consolidation (2024-2029), and Operations Phases (2030 and beyond) will be similar to the lunar outpost development. The dates for these phases and the applications are only approximate.

The planetary applications were divided into fixed and portable systems. As seen in Tables 1 (Moon) and 2 (Mars), fixed applications included communications stations, base main power, and lander servicers (LEV and MEV). Portable or mobile applications included the payload unloader, unpressurized rover with power cart (manned or unmanned), pressurized manned rover with power cart, mining hauler, mining excavator, and telerobotic rover (Mars only). There were a total of 6 different fixed lunar power systems, 5 mobile lunar power systems, 5 fixed Mars systems, and 6 portable Mars systems. Scientific and in-situ resource utilization applications received their power from the base main power system.

Mining vehicles (excavator and hauler) were added to the Mars applications (Ref. 3). Also, a high power system was not included to provide power to industrial processing plants for the utilization phase on the Mars since requirements for this system have not as yet been estimated.

Dedicated backup or emergency power systems were included in this study for the permanent bases to provide life support to the habitat. It is assumed that mobile vehicles and/or the landers can provide this function, if necessary, for the Mars exploration sites. Reference 2 assumes that the unpressurized rover power cart can be used for emergency habitat power. However, Rocketdyne has opted for a dedicated power system of 12 kWe to insure that emergency power is available when needed without impacting full utility of the unpressurized rover (Ref. 5).

Power system requirements were defined for the remainder of the applications using various NASA references (Refs. 1, 2, 3, and 6) and engineering judgement (where data was not available). These requirements included IOC (sometimes more than one date due to multiple launch dates; the earliest IOC was used for power system technology matching), power levels (nominal, peak, and standby), duty cycle (nominal power, peak power, and standby power duration), useful energy storage (actual energy storage depends on storage and discharge efficiencies), and the number of power systems required.

TABLE 1. - LUNAR MISSION APPLICATIONS AND REQUIREMENTS

Application No.	Description	IOC	Mission Phase *	Power - Nominal/ Peak/ Standby (kWe)	Time - Nom./ Peak/ Stand-by (hrs)**	Operating Time	No. of Units ***
	FIXED POWER:						
L1	Communications	1999	EMP	0.9		D/N	1
L2	Base Power	2000, 2001	EMP	25 (D) 12.5(N)		D/N	3
L3	Emergency Power	2000	EMP	12		D/N	1
L4	LEV Servicer	2002, 2003	EMP CON	10		D/N	3
L5	Base Power	2003	CON	100		D/N	1
L6	Base Power	2008	OP	550/550		D/N	1
	MOBILE POWER:						
L7	Payload Unloader	1999	EMP	3/10	9/1	D	2
L8	Unpressurized Rover	1999, 2001, 2012	EMP EMP OP	5+	24	D/N	3
L9	Press. Manned Rover, Power Cart for Rover	2004	CON	7 12++	8 96	D/N D/N	1 1
L10	Regolith Hauler	2008	OP	3/15/1.5	8/1/1.4	D	1
L11	Mining Excavator	2008	OP	22/40/10	8/1/1.4	D	1

NA - information not available. D=day, N=night.
*EMP=Emplacement Phase, CON=Consolidation Phase, OP=Operations Phase.
**24 hour cycle for mobile power systems except for L9.
***Does not include replacement units.
+Actual rover requirements are 2(nominal).3(peak)/0.3(standby) kWe. A requirement of 5 kWe was selected by NASA (Ref. 2) to provide night habitat power prior to delivery of main base power system and also recharging for payload unloader.
++Cart power. Can be 5 kWe if isotope power system used for onboard power.

Lunar power system requirements spanned a wide range from 0.9 to 550 kWe. Mars power requirements spanned a smaller range from 0.9 to 75 kWe. The portable system power requirements were assumed to be the same for both lunar and Mars applications. Base and some portable system energy storage requirements were greatly reduced for Mars applications due to the shorter night time period (12 hours versus 354 hours).

TABLE 2 - MARS APPLICATIONS AND POWER SYSTEM REQUIREMENTS

Application No.	Description	Mission Phase *	IOC	Power - Nominal/ Peak/ Standby (kWe)	Time - Nom./ Peak/ Stand-by (hrs)**	Operating Time	No. of Units ***
	FIXED POWER:						
M1	Communications	EX	2016, 2018, 2020	0.9		D/N	3
M2	Base Power	EX	2016, 2018, 2020	25		D/N	3
M3	Emergency Power	EMP	2022	12		D/N	1
M4	MEV Servicer	EMP	2022	10		D/N	1
M5	Base Power	EMP	2022	75		D/N	1
	MOBILE POWER:						
M6	Unpress. Rover with Power Cart	EXP	2016, 2018, 2020	5+	24.65	D/N	5
M7	Payload Unloader	EMP	2022	3/10	7/1	D	3
M8	Telerobotic Rover	CON	2024	0.15/1.5	24.42/0.23	D/N	1
M9	Pressurized Rover, Power Cart for Rover	CON	2026	7 12++	8 96	D/N D/N	1 1
M10	Regolith Hauler	OP	2030	3/15/1.5	5.6/1/1.4	D	1
M11	Mining Excavator	OP	2030	22/40/10	5.6/1/1.4	D	1

NA - information not available. D=day, N=night.
*EXP=Exploration Phase, EMP=Emplacement Phase, CON=Consolidation Phase, OP=Operations Phase.
**24 hour cycle for mobile power systems except for M11.
***Does not include replacement units.
+Actual rover requirements are 2(nominal)/3(peak)/0.3(standby) kWe. A requirement of 5 kWe was selected by NASA (Ref. 2) to provide night habitat power prior to delivery of main base power system and also recharging for payload unloader.
++Cart power. Can be 5 kWe if isotope power system used for onboard power.

The bases and exploration sites were assumed to be near the equator. Thus, the day and night times for both Mars and lunar applications were assumed to be equal.

Recharging power for energy storage systems were assumed to be provided by the base PVA power system. The duty cycle assumed (i.e., charging times), combined with low system efficiencies (as for the RFC systems examined), may require excessive power drain on the overall base power capabilities for rechargeable mobile power systems. Tables 3 and 4 show the powers required for recharging RFC energy storage systems based on the specified recharging times.

Duty cycles for portable applications were based primarily on previous NASA studies (Refs. 2 and 6). A short recharge time of 2 hours (Ref. 2) was originally selected for the pressurized rovers to provide the crew "safe haven" in the event of a habitat failure. However, the power system mass studies showed that a 2 hour recharge time would be an excessive mass penalty for RFC power systems (large radiator and large increase in base PVA) Thus, the recharge time for the pressurized rovers was assumed to equal the on time of 8 hours. The emergency power system could provide power to the pressurized rover as an alternative to a quick recharge of the rover power system. An equal discharge and recharge time is also assumed for the Mars portable power systems which do not operate continuously (i.e., payload unloader, regolith hauler, and mining excavator).

TABLE 3. - LUNAR RFC SYSTEM RECHARGING POWER REQUIREMENTS

Application No.	Description	Recharge Time (hrs)	RFC Roundtrip Cycle Efficiency (%)*	Electrolysis Stack Bus Power (kWe)
	FIXED POWER:			
L1	Communications	354	41	2.2
L2	Base Power	354	39	32.6
L3	Emergency Power	354	42	29.0
L4	LEV Servicer	354	43	23.4
L5	Base Power	NA	NA	NA
L6	Base Power	NA	NA	NA
	MOBILE POWER:			
L7	Payload Unloader	14	40	6.7
L8	Unpressurized Rover	NA	NA	NA
L9	Press. Manned Rover Power Cart for Rover	8 48	40 41	17.5 58.5
L10	Regolith Hauler	13.6	36	8.3
L11	Mining Excavator	13.6	39	43.8

*Includes fuel cell, electrolysis cell, PMAD, pumping, and gas cooling losses (approximately 12%); end-of-mission performance.
NA=not applicable to energy storage systems due to excessive mass.

TABLE 4. - MARS RFC SYSTEM RECHARGING POWER REQUIREMENTS

Application No.	Description	Recharge Time (hrs)	RFC Roundtrip Cycle Efficiency (%)*	Electrolysis Stack Bus Power (kWe)
	FIXED POWER:			
M1	Communications	12.325	40	2.2
M2	Base Power	12.325	40	63.0
M3	Emergency Power	12.325	38	31.6
M4	MEV Servicer	12.325	38	26.5
M5	Base Power	12.325	37	200.5
	MOBILE POWER:			
M6	Unpressurized Rover	NA	NA	NA
M7	Payload Unloader	8	40	9.8
M8	Telerobotic Rover	NA	NA	NA
M9	Pressurized Rover, Power Cart for Press. Rover	8 96	40 43	17.5 28.0
M10	Regolith Hauler	8	41	10.2
M11	Mining Excavator	8	40	55.5

*Includes fuel cell, electrolysis cell, PMAD, pumping, and gas cooling losses (approximately 12%); end-of-mission performance.
NA=not applicable to energy storage systems due to excessive mass.

3.4 POWER SYSTEM CONCEPT SYNTHESIS AND PRELIMINARY SCREENING

The power system synthesis process involved identifying potential subsystem technologies. Subsystem compatibility was used to match energy sources (nuclear and solar) and power conversion units (static and dynamic). Nineteen different power system candidates were synthesized which seemed the most promising for planetary applications. Both standalone power systems (i.e., including energy source) and rechargeable power systems were defined as shown in Table 5.

TABLE 5. - SCREENED POWER SYSTEM CONCEPTS

System No.	Source	Power Converter	Energy Storage Unit	Radiator
1	Sun	Ga As/Ge PVA	PEM RFC	Heat pipe
2A	Sun	Ga As/Ge PVA	NiH_2 Battery	Heat pipe
2B	Sun	Ga As/Ge PVA	NaS Battery	Heat pipe
2C	Sun	Ga As/Ge PVA	Flywheel/PMG	Heat pipe
3	Concentrator/Receiver	CBC	RFC	Heat pipe
4	Concentrator/Receiver	Stirling	RFC	Heat pipe
5	Isotope	CBC		Tube sheet
6	Isotope	Stirling		Heat pipe
7	Isotope	AMTEC		Heat pipe
8	LMC Reactor	Thermoelectric		Heat pipe
9	LMC Reactor	Stirling		Heat pipe
10	LMC Reactor	CBC		Heat pipe
11	LMC Reactor	AMTEC		Heat pipe
12	In-Core Therm. Reactor	Thermionics		Heat pipe
13 *			RFC	Heat pipe
14A *			NiH_2 Battery	Heat pipe
14B *			NaS Battery	Heat pipe
15 *			Flywheel/PMG	Heat pipe
16	Isotope	Thermoelectric		Conduction

*Similar to systems 1, 2A, 2B, and 2C except that energy storage is recharged from base PVA power system.

Additional variations were defined for some of the nineteen different power system candidates as shown in Table 6. For example, dynamic power systems with different peak converter temperatures were identified for different technology levels (Ref. 7). The 1033 °K temperature represents the well demonstrated technology associated with programs such as Brayton Rotating Unit (BRU) and Brayton Isotope Power System (BIPS). The 1133 °K temperature environment represents a maximum performance limit of super alloys. The highest technology level identified is given as 1300 °K which represents an optimum performance level with advanced refractory alloys and maintains adequate margins for the current GPHS module temperature limits.

Launch availability for power systems were categorized by time frames as shown in Table 6. Practical power ranges or power limits are also shown in Table 6.

3.5 POWER SYSTEM ENVIRONMENTAL IMPACTS AND DESIGN OPTIONS

Only a limited study of environmental impacts was completed. The purposes of this study were the following:

- determine the compatibility of lunar power systems to the Mars environment; and
- determine the impact of design changes due to the Martian environment on power system concept mass and size.

Various design options were investigated to allow "commonality" between lunar and Mars applications. These changes to the reference module designs were grouped into three categories: minor, moderate, and major. Minor changes included coatings or extra containment for one portion of the flow circuit. Moderate changes require more development cost and include incorporation of protective enclosures (insulation and stainless steel enclosure, vacuum bottle, or inert gas enclosure) or seals around components to shield against corrosion, dust (loose piping before assembly or during servicing), or aerodynamic drag (rotating machinery). Moderate changes may also require scaling of various components (i.e., radiators need to be scaled for

TABLE 6. - POWER SYSTEM TECHNOLOGY LEVELS AND POWER RANGES

Power System Number	Description	Peak Converter Temp.(°K)	System Technology Level	Module Power Range* (kWe)
1	PVA/Regenerative Fuel Cell		MT	≤100
2A	PVA/Nickel Hydrogen Battery		NT	≤100
2B	PVA/Sodium Sulfur Battery		MT	≤100
2C	PVA/Flywheel/PMG		MT	≤100
3A	SD/CBC/RFC	1133	MT	≤150
3B	SD/CBC/RFC	1300	MT	≤150
4A	SD/Stirling/RFC	1033	MT	≤150
4B	SD/Stirling/RFC	1300	FT	≤150
5A	Isotope/CBC	1133	NT	≤25
5B	Isotope/CBC	1300	MT	≤25
6A	Isotope/Stirling	1033	MT	≤25
6B	Isotope/Stirling	1300	FT	≤25
7	Isotope/AMTEC	1300	FT	≤25
8	LMCR/Thermoelectric	1300	MT	≥25
9A	LMCR/Stirling	1033	MT	≥25
9B	LMCR/Stirling	1300	FT	≥25
10A	LMCR/CBC (SNAP-DYN)	922	NT	≥25
10B	LMCR/CBC	1133	NT	≥25
10C	LMCR/CBC	1300	MT	≥25
11	LMCR/AMTEC	1300	FT	≥25
12	In-Core Thermionic Reactor	1100	MT	≥25
13	Regenerative Fuel Cell		NT	≤25
14A	Nickel Hydrogen Battery		NT	≤25
14B	Sodium Sulfur Battery		MT	≤25
15	Flywheel/Motor-Generator		MT	≤25
16	RTG (MOD)		NT	≤1

*Approximate values given; the upper limits depend on environment and application (fixed or mobile).

different heat sink temperature and PVA requires more surface area due to the lower solar insolation on Mars). Major design changes resulting in major development cost increases may include use of lower operating temperatures to allow the use of non-refractory metals for corrosion prevention in the Martian atmosphere. Further study is needed to evaluate the tradeoffs between these approaches and to select the optimum.

For this study, the reactor options for Mars applications which were evaluated included a stainless steel liquid metal cooled reactor with a dynamic power conversion unit, an SP-100 reactor with a vacuum enclosure, and an in-core thermionic reactor (also referred to as driver fuel thermionic since there is extra driver fuel in the core in addition to the fuel in the thermionic converter elements). The stainless steel reactor must operate at a reduced temperature (1033 °K or less) from the SP-100 reactor (1300 °K). The stainless steel reactor power conversion system efficiency is reduced and the radiator size is increased due to the lower peak temperature. This factor significantly increases power system mass for lower temperature systems compared to the 1300 °K or higher power systems. These factors and others make the liquid metal cooled reactor system higher in mass than the in-core thermionic reactor system. The thermionic reactor operates at a temperature (1100 °K) which is suitable for the use of stainless steel for the containment vessel and piping. Thus, a special enclosure is not required for the thermionic reactor for Mars. The high rejection temperature for the thermionic converters also reduces radiator size and system mass.

The SP-100 system, as currently designed, is not suitable for Mars applications since the refractory metals used are not compatible with the carbon dioxide environment. Design modifications to the SP-100 system for Mars which were examined included coatings of high temperature components and a vacuum enclosure for the reactor. Coatings may not remain totally protective for long duration high temperature operation. The vacuum enclosure option for the reactor may be possible, but issues include the potential for single point failure (puncture or loss of seal), and the mass penalty of the structure and pumping system. The reactor power system concept masses are compared in Figure 2 as a function of output power. The masses in Figure 2 represent approximate values since they do not include shield mass or secondary loop mass. The SNAP-DYN numbers assume a peak fluid temperature of 922 °K. No replacement system masses are included in Figure 2.

Isotope power systems can be fairly easily adapted for the Martian environment. The approaches are either to (1)run at reduced temperature so that super alloys can be used or (2)use an extra enclosure for the fluid loop from the heat source heat exchanger to the turbine (for Brayton cycle). The first approach is likely to be developed anyway for nearterm and midterm applications. However, the mass and radiator size of the lower temperature systems would be higher than for the latter option. Again, there is the potential for single point failure with the second approach. However, there would normally be redundant fluid loops and power conversion units for dynamic isotope systems.

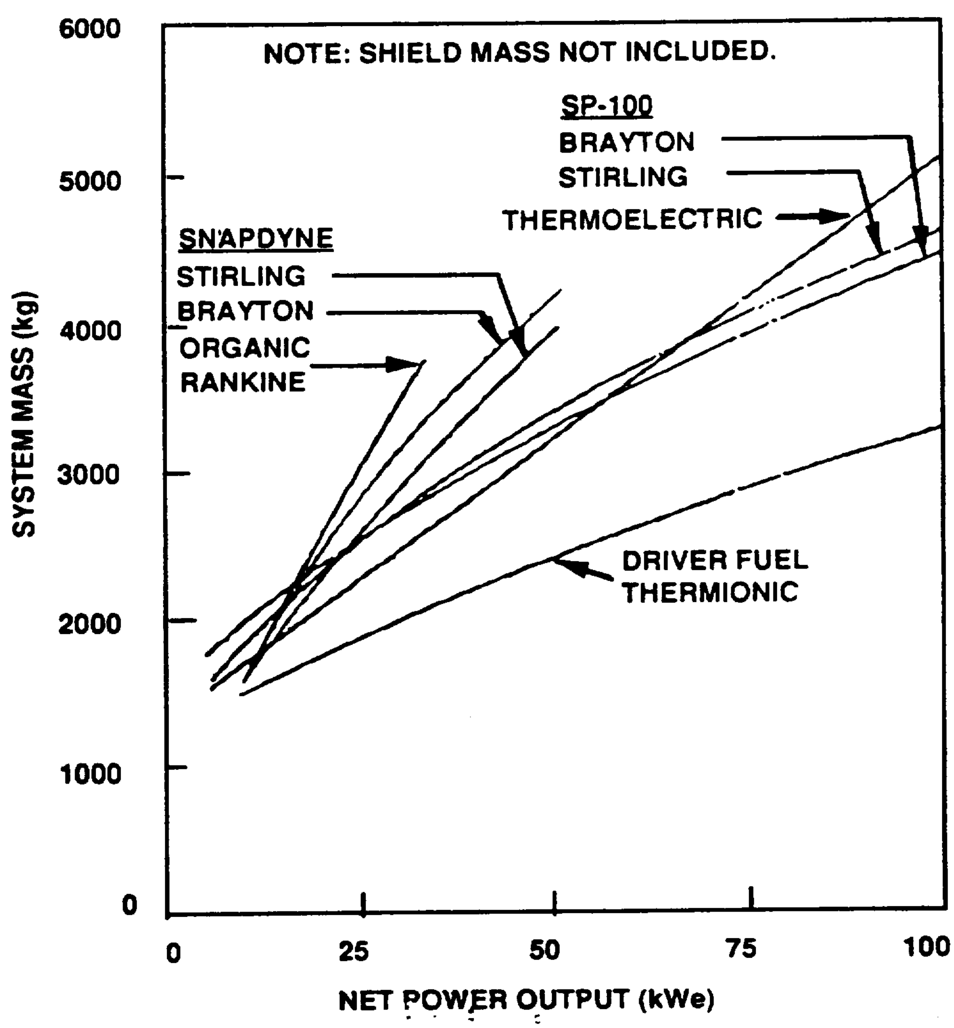

Figure 2. - Mars power system mass comparison (approximate numbers).

3.6 POWER SYSTEM APPLICABILITY

Each planetary activity was assigned an availability requirement based on the earliest IOC date. Power system applicability matrices, Figures 3 and 4 were then defined by comparing activity requirements (Tables 1 and 2) with power system availability and capabilities (Table 6). In addition, energy storage mass competitiveness, environmental compatibility, and safety (excessive mitigation measures required for protecting personnel) were used as screening criteria. Both the power system availability timeframe and application timeframes (launch IOC) are shown in Figures 3 and 4 for comparison. Applicable power systems are indicated by a √ mark.

Safety criteria dictated that there be no reactors on vehicles or near manned areas (habitat, lander, science, in-situ resource utilization). Thus, either non-reactor power sources or distribution of power from a remote reactor power system is required for these applications.

Only remote or portable power systems were assigned to the communications and lander areas. This meant the use of PV or isotope systems for these areas.

The energy storage subsystem mass comparison study showed that only RFC systems are currently practical for lunar base fixed power (< 100 kWe) due to the large night time energy storage requirements. Thus, batteries and flywheels are only applicable to short duration applications such as vehicles or portable equipment and Mars applications.

Lower temperature reactor systems with suitable structural materials (i.e., stainless steel as in the Rocketdyne SNAP-DYN system), an enclosed SP-100 system, and in-core thermionic reactors (no exposed refractory metals) are applicable to Mars.

It was assumed that PV arrays would not be carried on the portable applications (energy storage assumed to be recharged by base PVA power system). It is assumed that all vehicles and portable equipment will be used near the base and will return to the base for recharging, or will use an isotope system.

Finally, solar dynamic systems which collect and concentrate light energy, will not work very well on Mars since much of the time the solar energy is in a diffuse rather than beam type nature. During global dust storms, the solar energy becomes totally scattered light. Concentrators for photovoltaic systems offer no benefit on Mars for the same reason.

			Fixed Applications						Mobile Applications				
Application ⇒ **Power System** ⇓	PCU Peak Temp. (K)	Avail-ability (IOC)	L1	L2	L3	L4	L5	L6	L7	L8	L9	L10	L11
Power (kWe) ⇒			0.9	25/ 12.5	12	10	100	550	3	5	7, 12	3	22
Mission IOC ⇒			NT	MT	MT	MT	MT	MT	NT	NT	MT	MT	MT
1-PVA/RFC		MT		√	√	√	√						
3A-ST/CBC/RFC	1133	MT		√	√	√	√						
3B-ST/CBC/RFC	1300	MT		√	√	√	√						
4A-ST/SC/RFC	1033	MT		√	√	√	√						
5A-Isotope/CBC	1133	NT	√		√	√			√	√	√	√	√
5B-Isotope/CBC	1300	MT			√	√					√	√	√
6A-Isotope/SC	1033	MT			√	√					√	√	√
8-LMCR/TE	1300	MT		√			√						
9A-LMCR/SC	1033	MT		√			√	√					
10A-LMCR/CBC	922	NT		√									
10B-LMCR/CBC	1133	NT		√			√	√					
10C-LMCR/CBC	1300	MT		√			√	√					
12-In-Core TI	1100	MT		√			√	√					
13-RFC		NT									√	√	√
14A-NiH2 Battery		NT							√		√	√	√
14B-NaS Battery		MT									√	√	√
15-Flywheel/PMG		MT									√	√	√

Figure 3. - Power system applicability matrix - lunar applications.

From Figure 3, it can be seen that various systems were not applicable for lunar applications including PVA/battery (excessive weight), PVA/flywheel (excessive weight), ST/SC/RFC (1300 °K not available), I/SC (1300 °K not available), I/AMTEC (not available), LMCR/AMTEC (not available), and RTG (power levels too high). From Figure 4, it is seen that systems not applicable for the Mars power systems included all the solar thermal systems (insufficient solar beam energy). The refractory metal, liquid-metal cooled reactor systems are tentatively assumed to be applicable, but only if protected from the Mars environment. Additional reactor studies are needed to determine what type of enclosure or protection method is practical.

			Fixed Applications					**Mobile Applications**					
Application ⇒ **Power System ⇓**	PCU Peak Temp. (K)	Avail-ability (IOC)	M1	M2	M3	M4	M5	M6	M7	M8	M9	M10	M11
Power (kWe) ⇒			0.9	25	12	10	75	5	3	0.15	7, 12	3	22
Mission IOC ⇒			FT	FT	AD	AD	AD	FT	AD	AD	AD	AD	AD
1-PVA/RFC		MT	√	√	√	√	√						
2A-PVA/NiH2 Battery		NT	√	√	√	√	√						
2B-PVA/NaS Battery		MT	√	√	√	√	√						
2C-PVA/Flywheel		MT	√	√	√	√	√						
5A-Isotope/CBC	1133	NT	√		√	√		√	√	√	√	√	√
5B-Isotope/CBC	1300	MT	√		√	√		√	√	√	√	√	√
6A-Isotope/SC	1033	MT	√		√	√		√	√	√	√	√	√
6B-Isotope/SC	1300	FT	√		√	√		√	√	√	√	√	√
7-Isotope/AMTEC	1300	FT	√		√	√		√	√	√	√	√	√
8-LMCR/TE*	1300	MT		√			√						
9A-LMCR/SC	1033	MT		√			√						
9B-LMCR/SC*	1300	FT		√			√						
10A-LMCR/CBC	922	NT		√			√						
10B-LMCR/CBC*	1144	NT		√			√						
10C-LMCR/CBC*	1300	MT		√			√						
12-In-Core TI	1100	MT		√			√						
13-RFC		NT							√		√	√	√
14A-NiH2 Battery		NT							√		√	√	√
14B-NaS Battery		MT							√		√	√	√
15-Flywheel/PMG		MT							√		√	√	√
16-RTG (MOD)		NT								√			

*Assumes reactor is in vacuum enclosure.

Figure 4. - Power system applicability matrix - Mars applications.

3.7 POWER SYSTEM GENERIC COMMONALITY

There were two areas of interest in the commonality evaluation of the power systems over the entire scenario. The first was how often each power system might be utilized. This evaluation was done quantitatively using the application matrix (number of occurrences divided by number of power systems required). The other area of interest was how much different the power system would be for common applications (i.e., could the reference design be used or does the system have to be modified?).

Figure 5 shows the methodology used for evaluating commonality on a system and architecture basis. A decision model was developed to determine the evaluation criteria and the methods for evaluating the criteria. Criteria was developed for rating generic power system commonality (i.e., not architecture specific) and synthesizing power system architectures. Only the generic commonality of each power system relative to the application scenario was evaluated. The generic commonality approach allows a power system concept to be applied wherever it is feasible as defined by the power system application matrix.

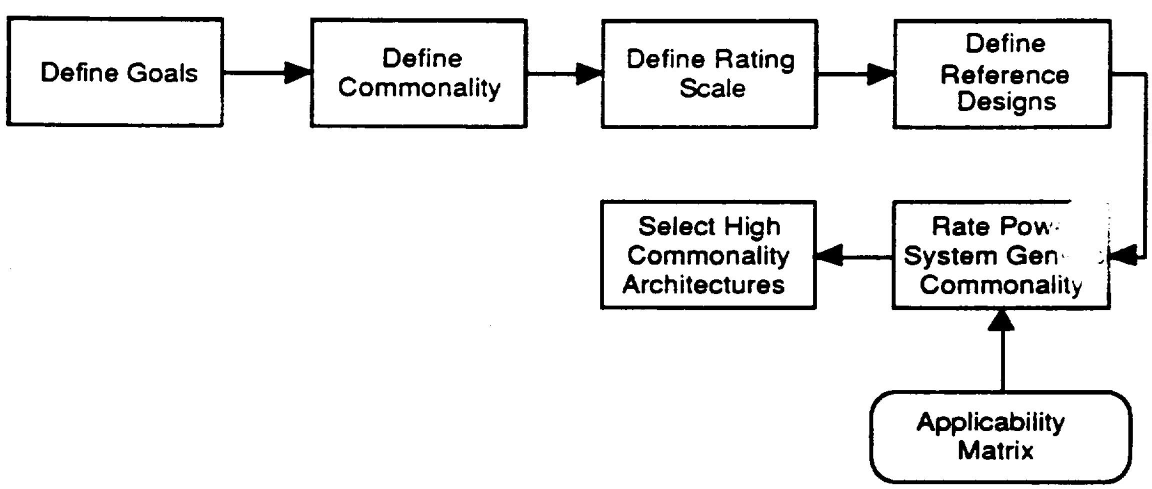

Figure 5. - Commonality evaluation flow logic diagram.

To evaluate the power system commonality, a linear rating scale was developed for evaluating common power system applications. Rating scales based on a semi-quantitative evaluation were used to rate each power system/application relative to the reference system design. The different commonality levels were based on increasing development cost (subjective assessment relative to reference design/size). The rating levels were defined as follows:

- <u>Level 4</u> - The same power system or multiple modules may be used **(FOM = 1.00)**
- <u>Level 3</u> - Minor component level or subsystem design changes. No system requalification requires **(FOM = 0.67)**
- <u>Level 2</u> - Major subsystem changes for more than one subsystem. System requalification required **(FOM = 0.33)**
- <u>Level 1</u> - Totally new power system required **(FOM = 0.00)**

The rating levels were then converted to a figure of merit (FOM) value as shown in Figure 6. The average FOM was then determined for each concept over the entire scenario (also for the lunar and Mars portions alone). The FOM was used as a derating factor on the raw commonality result for each power system to account for additional development costs due to potential differences in design for each application. Actual development costs were not estimated for this study.

Reference power systems were selected for each concept to meet the earliest timeframe and highest power level application. For example, concepts 1, 3, and 4 used application L2 for the reference design requirements. All power system designs were compared with the reference system for each power system concept to determine the applicable FOM.

Once a power system design has been developed, system requalification may not be required for scaling of systems to different power levels. Scaling may be desirable to minimize power system mass and architecture mass which minimizes transportation cost. It is also desirable to be able to use one of the reference designs for each of the mission scenario applications to minimize development costs.

To illustrate the approach used in evaluating generic power system commonality, an example calculation is discussed in the following section.

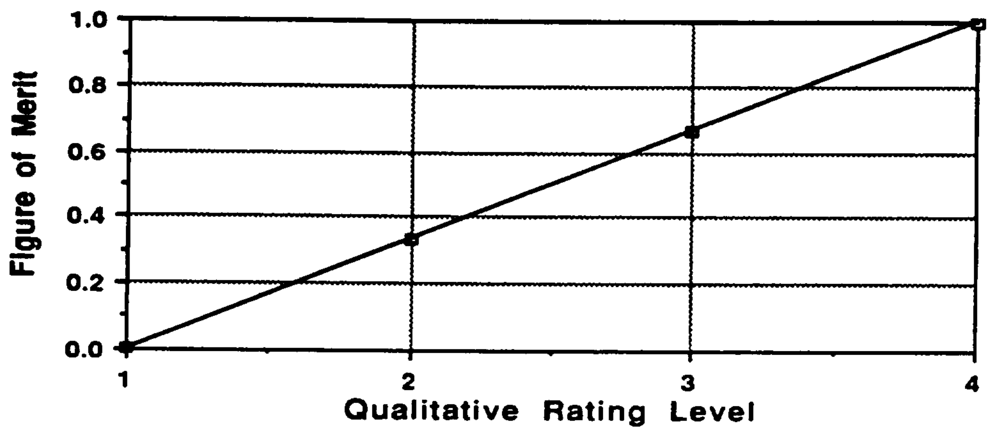

Figure 6. - Concept commonality rating scale.

3.7.1 <u>Commonality Calculation</u>

Applicability of a power system to each mission is checked first using Figures 3 and 4. The power system design is compared with the "reference system" which represents a specific power system design and technology. It is assumed for each power system that the reference system will be developed and that changes to the reference system design will essentially result in new systems with additional development costs. Once a new system design or size has been developed, then this reference design is then added to the inventory of power systems.

The qualitative FOM rating scale is used to select the commonality level for the power system and mission combination. Credit is given in the commonality assessment for prior development of a "new system" (i.e., system not the same as the original reference system).

The figure of merit (FOM) rating for each system/application combination is determined by converting the linear qualitative ratings of 1 through 4 to corresponding numerical values of 0 to 1 using Figure 6.

The power system is rated for each applicable mission in the scenario using the same approach. The power system commonality rating is calculated for the lunar portion of the scenario. This is essentially an average commonality rating as follows:

$$FOM_{Lunar} = \frac{\sum_{i=1}^{n}(\#\text{ of systems x FOM rating for mission})}{\text{number of lunar applications}}$$

The total number of lunar applications is the number of power systems (missions L1-L11) required including duplicate systems for a given mission .

Next, the power system commonality rating is determined for the Mars portion of the scenario using the same approach as for the lunar missions. The results are as follows:

$$FOM_{Mars} = \frac{\sum_{i=1}^{n}(\#\text{ of systems x FOM rating for mission})}{\text{number of Mars applications}}$$

The total number of Mars applications is the number of power systems (missions M1-M11) required including duplicate systems for a given mission .

Finally, the power system commonality rating for the entire scenario is determined as follows:

$$FOM = \frac{19^{*}FOM_{Lunar}+22^{*}FOM_{Mars}}{41}$$

3.7.2 Generic Commonality Results

Tables 7 and 8 show the commonality ratings for each screened power system option/mission combination. The ratings range from a qualitative rating level of 1 to 4. For applications which are not considered applicable, the qualitative ratings are "1" which correspond to FOM value of 0. These ratings have not been shown on the chart. The overall power system ratings for the entire mission scenario are shown in Table 9. These ratings represent the relative usefulness (applicability, availability, commonality) for a given concept relative to planetary applications.

TABLE 7. - GENERIC POWER SYSTEM COMMONALITY RATINGS FOR LUNAR APPLICATIONS

			Fixed Applications						Mobile Applications				
Application ⇒ **Power System ⇓**	PCU Peak Temp. (K)	Avail-ability (IOC)	L1	L2	L3	L4	L5	L6	L7	L8	L9	L10	L11
Power (kWe) ⇒			0.9	25/ 12.5	12	10	100	550	3	5	7, 12	3	22
Mission IOC ⇒			NT	MT	MT	MT	MT	MT	NT	NT	MT	MT	MT
1-PVA/RFC		MT		4	3	3	4						
3A-SD/CBC/RFC	1133	MT		4	3	3	4						
3B-SD/CBC/RFC	1300	MT		4	3	3	4						
4A-SD/SC/RFC	1033	MT		4	3	3	4						
5A-Isotope/CBC	1133	NT	4		3	3			3	3	3	3	3
5B-Isotope/CBC	1300	MT			4	3					3	3	3
6A-Isotope/SC	1033	MT			4	3					3	3	3
8-LMCR/TE	1300	MT		4			4						
9A-LMCR/SC	1033	MT		2			3	4					
10A-LMCR/CBC	922	NT		4									
10B-LMCR/CBC	1133	NT		2			3	4					
10C-LMCR/CBC	1300	MT		2			3	4					
12-In-Core TI	1100	MT		3			3	4					
13-RFC		NT							4		3	3	3
14A-NiH2 Battery		NT							4		3	3	3
14B-NaS Battery		MT									3	3	4
15-Flywheel/PMG		MT									3	3	4

TABLE 8. - GENERIC POWER SYSTEM COMMONALITY RESULTS FOR MARS APPLICATIONS

Application ⇒ / Power System ⇓	PCU Peak Temp. (K)	Avail-ability	Fixed Applications					Mobile Applications					
			M1	M2	M3	M4	M5	M6	M7	M8	M9	M10	M11
Power (kWe) ⇒			0.9	25	5	10	75	5	3	0.15	7, 12	3	22
Mission IOC ⇒			FT	FT	AD	AD	AD	FT	AD	AD	AD	AD	AD
1-PVA/RFC		MT	3	3 *	3	3	4						
2A-PVA/NiH2 Battery		NT	3	3 *	3	3	4						
2B-PVA/NaS Battery		MT	3	3 *	3	3	4						
2C-PVA/Flywheel		MT	3	3 *	3	3	4						
5A-Isotope/CBC	1133	NT	3		3	3		3 *	3	3	3	3	3
5B-Isotope/CBC	1300	MT	3		3	3		3 *	3	3	3	3	3
6A-Isotope/SC	1033	MT	3		3	3		3 *	3	3	3	3	3
6B-Isotope/SC	1300	FT	3		3	3		3 *	3	3	3	3	3
7-Isotope/AMTEC	1300	FT	3		3	3		3 *	3	3	3	3	3
8-LMCR/TE**	1300	MT		3 *			4						
9A-LMCR/SC	1033	MT		3 *			3						
9B-LMCR/SC**	1300	FT		4			3						
10A-LMCR/CBC	922	NT		3 *			3						
10A-LMCR/CBC**	1133	NT		3 *			3						
10A-LMCR/CBC**	1300	MT		3 *			3						
12-In-Core TI	1100	MT		3 *			3						
13-RFC		NT							3 *		3	4	3
14A-NiH2 Battery		NT							3 *		3	4	3
14B-NaS Battery		MT							3 *		3	4	3
15-Flywheel/PMG		MT							3 *		3	4	3
16-RTG (MOD)		NT								4			

*Modified lunar system. Becomes new reference system for Mars applications.
**Enclosed reactors.

TABLE 9. - OVERALL POWER SYSTEM GENERIC COMMONALITY RATINGS

Power Systems		Lunar Ratings	Mars Ratings	Overall Ratings
1-PVA/RFC		0.35	0.29	0.32
2A-PVA/NiH2 Battery		0.00	0.29	0.15
2B-PVA/NaS Battery		0.00	0.29	0.15
2C-PVA/Flywheel		0.00	0.29	0.15
3A-SD/CBC/RFC	(1133 °K)	0.35	0.00	0.16
3B-SD/CBC/RFC	(1300 °K)	0.35	0.00	0.16
4A-SD/SC/RFC	(1033 °K)	0.35	0.00	0.16
5A-Isotope/CBC	(1133 °K)	0.74	0.77	0.76
5B-Isotope/CBC	(1300 °K)	0.42	0.77	0.61
6A-Isotope/SC	(1033 °K)	0.42	0.77	0.61
6B-Isotope/SC	(1300 °K)	0.00	0.77	0.41
7-Isotope/AMTEC		0.00	0.77	0.41
8-LMCR/TE		0.21	0.09	0.15
9A-LMCR/SC	(1033 °K)	0.18	0.12	0.15
9B-LMCR/SC	(1300 °K)	0.00	0.17	0.09
10A-LMCR/CBC	(950 °K)	0.05	0.12	0.09
10B-LMCR/CBC	(1133 °K)	0.18	0.09	0.13
10C-LMCR/CBC	(1300 °K)	0.18	0.09	0.13
12-In-Core TI		0.19	0.12	0.15
13-RFC		0.16	0.23	0.20
14A-NiH2 Battery		0.25	0.23	0.24
14B-NaS Battery		0.16	0.23	0.20
15-Flywheel/PMG		0.16	0.23	0.20
16-RTG		0.00	0.05	0.02

After rating each system, the concepts were grouped into 3 categories as seen in Table 10 based on a subjective evaluation. These results were then used to screen out low commonality/modularity systems from further consideration in the power system architecture studies. The systems which were retained are shown in the black box. The systems retained for further study included isotope (I/CBC, I/SC-1033 °K, RTG), PVA/RFC, RFC, NaS battery (only for DIPS peaking power), SP-100, in-core thermionic reactors, and dynamic SP-100 systems with vacuum enclosures. The RTG and dynamic SP-100 reactors were retained, despite low commonality ratings, since they were the only systems applicable to M9 and L5, respectively.

The isotope power systems, especially I/CBC, had the highest commonality ratings due to the approach taken in the DIPS program to design only 2.5 kWe modular power systems. This approach minimizes development cost and time with only a limited system mass penalty (for those systems requiring other than 2.5 kWe). The low temperature I/CBC power system, which is the baseline for the DIPS program, has wide applicability due to its early availability and good power range (from less than 1 kWe to perhaps 25 kWe). It was assumed that all isotope power systems would utilize the same modular development approach. There are currently no plans to develop an advanced DIPS (for example, a high temperature CBC or SC system). However, I/AMTEC is being examined as a possible replacement for RTG systems.

TABLE 10. - POWER SYSTEM GENERIC COMMONALITY RATING GROUPS*

Good (>0.31)	Fair (0.15-0.31)	Poor (<0.15)
I/CBC	RFC	LMCR/SC+
I/SC (1033 °K)	NaS Battery	LMCR/CBC+
PV/RFC	LMCR/TE	
	In-Core TI	
	I/SC (1300 °K)**	RTG
	I/AMTEC**	
	PVA/Battery**	
	PVA/Flywheel**	
	SD***	
	NiH2 Battery****	
	Flywheel****	

*Power systems within box retained for architecture studies.
**Deleted because of zero lunar commonality (cannot be tested for Mars applications).
***Deleted because of zero Mars commonality.
****Deleted because of excessive mass.
+Retained for L5.

3.8 POWER SYSTEM ARCHITECTURE STUDIES

Three power system architecture examples were defined as seen in Table 11 based on the highest commonality power systems of Table 10 and the applicability matrices of Figures 3 and 4.

Other power system architectures are possible, but generally with a lower commonality or higher mass. The purpose of this study, as stated previously, was not to determine the optimum architecture or power systems.

Architecture "A" is a highly PVA/RFC approach to meeting the power system requirements. Nuclear reactors are only used where PVA/RFC would not be practical from a mass and size standpoint. Isotope systems are used only for portable systems where continuous power is required (not practical to use energy storage alone due to mass) and for the lunar communications system (PVA/RFC system not available by 1999).

Architecture "B" is a highly nuclear/isotope approach using in-core thermionic reactors and DIPS. For the pressurized rovers, a 5 kWe DIPS carts was added to the onboard 7 kWe DIPS system to meet the total of 12 kWe needed for the 4 day trip requirement.

Architecture "C" is the same as "B" except that SP-100 TE and SP-100 dynamic reactor systems are used instead of in-core thermionic reactors.

A power system mass study was completed for each architecture. Masses, sizes, and operating conditions were determined. The mass results for each architecture and power system are shown respectively in Tables 12 to 14. The total mass of each architecture included all power systems (including multiple systems for each application). The highly incore thermionic reactor/isotope architecture (Architecture B) had the lowest mass.

TABLE 11. - HIGH COMMONALITY POWER SYSTEM ARCHITECTURE DEFINITIONS

Applic-ation	Description	Architecture "A"	Architecture "B"	Architecture "C"
	LUNAR FIXED POWER:			
L1	Communications (0.9 kWe)	DIPS*	DIPS	DIPS
L2	Base Power (25 kWe)	PVA/RFC	IN-CORE TI REAC.	SP-100
L3	Emergency Power(12 kWe)	PVA/RFC	DIPS	DIPS
L4	LEV Servicer (10 kWe)	PVA/RFC	DIPS	DIPS
L5	Base Power (100 kWe)	PVA/RFC	IN-CORE TI REAC.	SP-100 TE
L6	Base Power (550 kWe)	LMCR/CBC	IN-CORE TI REAC.	SP DYN. (1300 K)
	LUNAR MOBILE POWER			
L7	Payload Unloader (3 kWe)	RFC	DIPS	DIPS
L8	Unpressurized Rover with Power Cart (5 kWe)	DIPS	DIPS	DIPS
L9	Pressurized Rover, Power Cart for Rover	RFC (7 kWe) RFC (12 kWe)	DIPS (7 kWe) DIPS (5 kWe)	DIPS (7 kWe) DIPS (5 kWe)
L10	Regolith Hauler (3 kWe)	RFC	DIPS	DIPS
L11	Mining Excavator (22 kWe)	RFC	DIPS	DIPS
	MARS FIXED POWER:			
M1	Communications (0.9 kWe)	PVA/RFC	DIPS	DIPS
M2	Base Power (25 kWe)	PVA/RFC	IN-CORE TI REAC.	SP-100 TE**
M3	Emergency Power(12 kWe)	PVA/RFC	DIPS	DIPS
M4	MEV Servicer (10 kWe)	PVA/RFC	DIPS	DIPS
M5	Base Power (75 kWe)	PVA/RFC	IN-CORE TI REAC.	SP-100 TE**
	MARS MOBILE POWER:			
M6	Unpressurized Rover with Power Cart (5 kWe)	DIPS	DIPS	DIPS
M7	Payload Unloader (3 kWe)	RFC	DIPS	DIPS
M8	Teleoperated Rover (0.15 kWe)	DIPS	DIPS	DIPS
M9	Pressurized Rover, Power Cart for Rover	RFC (7 kWe) RFC (12 kWe)	DIPS (7 kWe) DIPS (5 kWe)	DIPS (7 kWe) DIPS (5 kWe)
M10	Regolith Hauler (3 kWe)	RFC	DIPS	DIPS
M11	Mining Excavator (22 kWe)	RFC	DIPS	DIPS

*DIPS = I/CBC (1133 °K).
**Enclosed reactor.

TABLE 12. - POWER SYSTEM ARCHITECTURE "A" MASS RESULTS

Appli-cations	Description	Power Systems	Power (D/N kWe)	Power Systems	Total Mass (kg)
	LUNAR MISSIONS				
L1	Communications	DIPS*	0.9/0.9	1	412
L2	Base Power -Emplacement	PVA/RFC	25/12.5	3	19,920
L3	Emergency Power	PVA/RFC	12/12	1	5,987
L4	LEV Servicer	PVA/RFC	10/10	3	15,003
L5	Base Power - Consolidation	PVA/RFC	100/100	1	49,550
L6	Base Power -Operation	LMCR/CBC (1300 °K)	550/550	1	15,901
L7	Payload Unloader	RFC	3/0.0	2	1,052
L8	Unpress. Rover with Power Cart	DIPS	5/5	3	2,472
L9	Pressurized Rover, Power Cart for Rover	RFC RFC	7/7 12/12	1 1	565 2,780
L10	Regolith Hauler	RFC	3/0.0	1	378
L11	Mining Excavator	RFC	22/0.0	1	1647
Subtotal - Lunar Missions					115,667
	MARS MISSIONS				
M1	Communications	PVA/RFC	0.9/0.9	3	909
M2	Base Power	PVA/RFC	25/25	3	22,203
M3	Emergency Power	PVA/RFC	12/12	1	3,679
M4	MEV Servicer	PVA/RFC	10/10	1	3,119
M5	Base Power	PVA/RFC	75/75	1	23,228
M6	Unpress.Rover with Power Cart	DIPS	5/5	5	4,420
M7	Payload Unloader	RFC	3/0.0	3	1,076
M8	Teleoperated Rover	DIPS	0.15/0.15	1	412
M9	Pressurized Rover, Power Cart for Rover	RFC, RFC	7/7 12/12	1 1	1,560 3,882
M10	Regolith Hauler	RFC	3/0	1	1,009
M11	Mining Excavator	RFC	22/0	1	4,912
Subtotal - Mars Missions					70,409
Scenario Total					186,062

*DIPS = I/CBC (1133 °K).

TABLE 13. - POWER SYSTEM ARCHITECTURE "B" MASS ESTIMATE

Appli-cation	Description	Power Systems	Power (D/N kWe)	Power Systems	Total Mass (kg)
	LUNAR MISSIONS				
L1	Communications	DIPS*	0.9/0.9	1	412
L2	Base -Emplacement	In-Core TI react.	75	1	4,125
L3	Emergency Power	DIPS	12/12	1	2,060
L4	LEV Servicer	DIPS	10/10	3	4,944
L5	Base-Consolidation	In-Core TI react.	100/100	1	4,700
L6	Base - Utilization	In-Core TI react.	550/550	1	9,700
L7	Payload Unloader	DIPS	3/0.0	2	1,648
L8	Unpress. Rover with Power Cart	DIPS	5/5	3	2,652
L9	Pressurized Rover, Power Cart for Rover	DIPS, DIPS	7/7 5/5	1 1	1,236 824
L10	Regolith Hauler	DIPS	3/0.0	1	1,034
L11	Mining Excavator	DIPS	22/0.0	1	4,142
Subtotal - Lunar Missions					37,477
	MARS MISSIONS				
M1	Communications	DIPS	0.9/0.9	3	1,236
M2	Base Power	In-Core TI Reac.	25/25	3	8,040
M3	Emergency Power	DIPS	12/12	1	2,060
M4	MEV Servicer	DIPS	10/10	1	1,648
M5	Base Power	In-Core TI Reac.	75/75	1	4,125
M6	Unpress.Rover with Power Cart	DIPS	5/5	5	4,420
M7	Payload Unloader	DIPS	3/0.0	3	2,472
M8	Teleoperated Rover	DIPS	0.15/0.15	1	412
M9	Pressurized Rover, Power Cart for Rover	DIPS, DIPS	7/7 5/5	1 1	1,236 824
M10	Regolith Hauler	DIPS	3/0	1	1,034
M11	Mining Excavator	DIPS	22/0	1	4,142
Subtotal -Mars Missions					31,649
Scenario Total					69,126

*DIPS = I/CBC (1133 °K).

TABLE 15. - POWER SYSTEM ARCHITECTURE "C" MASS ESTIMATE

Appli-cation	Description	Power Systems	Power (D/N kWe)	Power Systems	Total Mass (kg)
	LUNAR MISSIONS				
L1	Communications	DIPS*	0.9/0.9	1	412
L2	Base -Emplacement	SP-100	100	1	4,460
L3	Emergency Power	DIPS	12/12	1	2,060
L4	LEV Servicer	DIPS	10/10	3	4,944
L5	Base-Consolidation	SP-100	100/100	1	4,460
L6	Base - Utilization	LMCR/CBC(1300 °K)	550/550	1	16,400
L7	Payload Unloader	DIPS	3/0.0	2	1,648
L8	Unpress. Rover with Power Cart	DIPS	5/5	3	2,652
L9	Pressurized Rover, Power Cart for Rover	DIPS, DIPS	7/7 5/5	1 1	1,236 824
L10	Regolith Hauler	DIPS	3/0.0	1	1,034
L11	Mining Excavator	DIPS	22/0.0	1	4,142
Subtotal - Lunar Missions					44,272
	MARS MISSIONS				
M1	Communications	DIPS	0.9/0.9	3	412
M2	Base Power	SP-100**	25/25	3	9,630
M3	Emergency Power	DIPS	12/12	1	2,060
M4	MEV Servicer	DIPS	10/10	1	1,648
M5	Base Power	SP-100**	75/75	1	4,960
M6	Unpress.Rover with Power Cart	DIPS	5/5	5	4,420
M7	Payload Unloader	DIPS	3/0.0	3	824
M8	Teleoperated Rover	DIPS	0.15/0.15	1	412
M9	Pressurized Rover, Power Cart for Rover	DIPS, DIPS	7/7 5/5	1 1	1,236 824
M10	Regolith Hauler	DIPS	3/0	1	1,034
M11	Mining Excavator	DIPS	22/0	1	4,142
Subtotal -Mars Missions					31,602
Scenario Total					75,874

*DIPS = I/CBC (1133 °K).
**Enclosed reactor.

4.0 CONCLUSIONS/RECOMMENDATIONS

Based on the limited criteria used in this study it appears that development of PVA/RFC, NaS batteries, DIPS (modular 2.5 kWe 1133 °K CBC is the current baseline), reactor systems, and RFC systems should continue for planetary surface applications.

The SP-100 TE power system and dynamic PCU versions of SP-100 are suitable for lunar base power applications. Some development effort would be required to adapt the SP-100 system or dynamic PCU derivatives of SP-100 (based on operating temperatures used with lunar systems) to survive in the Martian carbon dioxide environment. A vacuum enclosed SP-100 system may be a viable approach. The in-core thermionic reactor is suitable for both lunar and Mars applications because of its lower operating temperature than the SP-100 system. However, there are significant development issues for the thermionic reactor (lifetime, serviceability, and flexibility to alternate power conversion systems).

Three high commonality power system architecture examples were defined in this study. There was a factor of over 3 difference in total delivered mass between the predominantly PVA/RFC vs. the predominantly nuclear/isotope option. Thus, high commonality does not necessarily mean low mass. Since transportation cost to the Moon and Mars generally outweighs development cost, low mass will tend to be a more important criteria than commonality for selecting the optimum power system architecture. Thus, this study ranked the highly nuclear/isotope architectures over the highly PV/RFC architecture due to reduced mass. However, it is felt that the architecture comparisons performed in this task, although suggestive, have not been performed to sufficient depth to select the optimum power system architecture. There are many additional criteria which must be considered in making this choice.

An additional, more detailed, ranking study is recommended to determine the optimum power system architecture using a more complete set of evaluation criteria (i.e., life cycle cost, risk, reliability/maintainability, and safety). The life cycle cost should include the transportation cost (mass driven), development, installation, decommissioning, and operating costs. The effect of different mission scenarios (i.e., aggressive vs less aggressive) on the optimum power system architecture should be determined. The interactions between power system selection and the architecture (i.e., effect of mobile RFC systems charging requirements on architecture mass including duty cycle tradeoffs) should be evaluated and optimized. Key mass drivers should be optimized in follow-on studies (i.e., radiators and energy storage). This will require a more in-depth study of system/component masses, costs, etc. Results of these recommended studies would allow definition of a development roadmap for planetary power systems.

5.0 REFERENCES

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